INFLUENCE OF PION-DELTA-HOLE CONFIGURATION ON THE RHO MESON MASS SPECTRUM IN DENSE HADRONIC MATTER

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Abstract

We discuss medium modification of the rho meson originating from its coupling to in medium quasi-pions and delta-hole states. This medium effect leads to a marked structure of the rho meson strength function in the $500\,MeV$ invariant mass region. We suggest that this effect may provide an explanation of the structure observed by the DLS collaboration in the $Ca + Ca/C + C$ ratio at $1\,GeV/u$.

The modification of the rho meson mass spectrum at finite density and/or temperature is a very vividly debated subject. The interest for vector mesons is certainly related to the expected relationship between the evolution of their properties especially their masses with the evolution of the glue and scalar condensates and chiral symmetry restoration in a hot and dense environment. In addition, dilepton production in relativistic heavy ion collisions provides, through a vector dominance picture, a unique tool to study the rho meson in highly excited matter. Indeed, data obtained at CERN/SPS by the CERES collaboration in $S + Au$ at $200\,GeV/u$ and $Pb + Au$ at $158\,GeV/u$ [1, 2] and the HELIOS collaboration [3] have revealed a significant amount of strength below the free rho meson peak in the invariant mass region of $500\,MeV$ [1, 2]. This led some authors to the conclusion that one is seing a downward shift of the rho meson mass induced by a QCD vacuum modification possibly intimately related to partial chiral symmetry restoration [4]. However it has been shown that more conventional many body mechanisms previously proposed in ref. [5, 6, 7] may explain the major part of the effect [8]. The main mechanism at work is the coupling of the rho meson to states made of collective pion branch and transverse delta-hole states (ie those $\Delta - h$ states excited in photo-reactions) [5, 8]. This mechanism alone cannot explain the whole effect but inclusion of the p-wave coupling of the rho to some higher nucleon or delta resonances, building up the so-called rhosobar [10], can give a reasonable agreement with data when incorporated in realistic calculation [9]. More recently, new DLS [11] data of dielectron cross section in nucleus-nucleus collisions at $1\,GeV$ have shown some striking features. In particular, the $Ca + Ca$ to $C + C$ ratio exhibits a marked structure in the $500 - 600MeV$ region. The purpose of this paper is to show that the original approach developed in ref. [5] for comparison with previous DLS data [12] (and subsenquently adapted to the CERN regime [8]) may provide, at least qualitatively, an explanation of the effect.

We will briefly summarize the formalism for the calculation of the in medium rho meson propagator, incorporating coupling to collective pionic modes, longitudinal and transverse $\Delta - h$ states and also $2p - 2h$ configurations. Then we will present some results for the ratio of the imaginary part of the rho meson propagator taken at two different densities and give a semi-quantitative discussion of the effect seen in the $Ca + Ca$ to $C + C$ ratio.

The rho meson propagator at momentum $q(q^0, \mathbf{q})$

$$G(q) = q^2 - m_\rho^2 - \Sigma(q) \tag{1}$$

is fully known once the self-energy $\Sigma(q)$ is known. In the model described in [5] this self energy is obtained by substracting the standard two-pion loop at $q = 0$ ensuring the proper normalization $F_\pi(0) = 1$ of the pion electromagnetic form factor. In free space it reads :

$$\Sigma(q) = \frac{4g^2}{3} \int \frac{d^3t}{(2\pi)^3} v^2(t) \frac{q^2}{4\omega_t^3} \frac{1}{q^2 - 4\omega_t^2 + i\eta} \tag{2}$$

with $\omega_t = (t^2 + m_\pi^2)^{1/2}$. The coupling coupling constant $g = 5$ and the parameter entering the form factor $v(t)$ have been fitted on the pion electromagnetic form factor and the $I = J = 1$ $\pi\pi$ phase shifts.

In the medium the rho self energy is modified by the dressing of the pion propagator through p-wave coupling to $\Delta - h$ states (fig. 1a) and various vertex correction (fig. 1b, c) necessary to ensure gauge invariance. In a two-level model the final result is entirely expressible in terms of the energy $\Omega_{1,2}(k)$ of two longitudinal collective modes built on pion and $\Delta - h$ states and two transverse modes with energy $\mathcal{E}_{1,2}(k)$. Here, we limit ourselves to the case where $\mathbf{q} = 0$:

$$\Sigma(q_0) = \Sigma_{LL}(q_0) + \Sigma_{LT}(q_0) \tag{3}$$

The first piece only depends on longitudinal modes :

$$\Sigma_{LL}(q_0) = \frac{4g^2}{3} \int \frac{d^3k}{(2\pi)^3} k^2 v^2(k) \sum_{i=j=1}^{2} \frac{q_0^2}{2(\Omega_i(k) + \Omega_j(k)) \Omega_i(k)\Omega_j(k)}$$

$$\times \left(1 + \frac{1}{2}(\alpha_i(k) + \alpha_j(k))\right)^2 \frac{Z_i(k) Z_j(k)}{q_0^2 - (\Omega_i(k) + \Omega_j(k))^2 + i\eta} \tag{4}$$

The eigenmodes $\Omega_1(k)$ are solution of the dispersion equation :

$$\Omega_i^2(k) - \omega_k^2 - k^2 \tilde{\Pi}^0(\Omega_i(k), \mathbf{k}) = 0 \tag{5}$$

where $\tilde{\Pi}^0(k^0, \mathbf{k})$ is the pion self-energy dominated by the p-wave coupling to the $\Delta - h$ states screened by short range correlations associated to the $g' = 0.5$ parameter. The explicit expression of $\Omega_i(k)$ and the associated weigth factors $Z_i(k)$ in the two-level model can be found in ref. [13]. From eq. (4), it can be seen that the $\rho - \pi\pi$ vertex is modified by the presence of the $\alpha_i(k) = \tilde{\Pi}^0(\Omega_i(k), \mathbf{k})$ factors. This vertex correction is represented by the diagram of fig. 1b and its net effect is to kill the structure at $q_0 = 2m_\pi$ originating from the dressing of the pions in the medium (fig. 1a) ; a detailed discussion can be found in [5].

The second piece of the in-medium self energy involves the coupling of the rho to the above longitudinal pionic modes and to a transverse mode, with energy $\mathcal{E}_i$ and strength Y_i, made of transverse delta-hole states and rho . In practice the collectivity of this states is very weak and the main contribution comes from the first state which is almost a pure transverse $\Delta - h$ state ($Y_1 \simeq 1$). Σ_{LT} reads :

$$\Sigma_{LT}(q_0) = \frac{4g^2}{3} \int \frac{d^3k}{(2\pi)^3} C(k) v^2(k) \sum_{i=j=1}^{2} \frac{q_0^2}{2(\Omega_i(k) + \mathcal{E}_j(k)) \Omega_i(k)\mathcal{E}_j(k)}$$

$$\times \frac{Z_i(k)\left(1 - Y_j(k)\right)}{q_0^2 - (\Omega_i(k) + \mathcal{E}_j(k))^2 + i\eta} \tag{6}$$

with $C(k)$ given by $C(k) = (8/9)(f^*_{\pi N\Delta}/m_\pi)^2 \mathcal{E}_{\Delta k} \Gamma^2_{\pi N\Delta(k)} \rho$ with notation of ref. [5]. The opening of this channel, depicted in fig. 1c, leads to a rather marked structure in the invariant mass region

$q_0 = M \geq m_\pi + \omega_\Delta \simeq 500\, MeV$ (see fig.2 and discussion below). This is the mechanism proposed in ref [8] to explain an important part of the observed enhancement in the CERES data. We will discuss in the following to which extent it can provide an explanation of the structure seen in the $Ca + Ca/C + C$ ratio measured by the DLS collaboration.

In practice the above results for the self-energy has to be improved by the inclusion of the width of the states. For instance, the width of the quasi-pion states is incorporated through the replacement :

$$\Omega_i(k) \rightarrow \Omega_i(k) + i\, \frac{\mathbf{k}^2\, Im\tilde{\Pi}^0(\Omega_i(k), \mathbf{k})}{2\, \Omega_i(k)} \tag{7}$$

and similar replacements for the transverse states. Here, the imaginary part of the irreducible pion self-energy $Im\tilde{\Pi}^0$, calculated along the dispersion line i, takes into account the delta width corrected from Pauli blocking [14] together with extra $2p - 2h$ contributions not reducible to a delta width [5]. The imaginary part of the self-energy Σ_{LL} and Σ_{LT} involving two-state propagators are now calculated using a spectral representation from which the real part is obtained by dispersion relation. All the details and phenomenological input are given in ref. [5].

The dilepton production is directly propotionnal to the strength function

$$S(q) = -\frac{Im\Sigma(q)}{|q^2 - m_\rho^2 - \Sigma(q)|^2} \tag{8}$$

This imaginary part of the rho meson propagator is shown on fig. 2 for several densities. The bump between 500 and 600 MeV reflects the the pion-transverse delta-hole intermediate states (see fig 1.c). In heavy ion reactions around $1 GeV/u$ incident energies, one can expect compressions of nuclei ranging from 1 to 2.5ρ_0 depending on the size of the system. To see how the structure at $500 - 600\, MeV$ evolves as a function of density, we show in figure 3 the ratio of the strength function (8) taken at two different densities typical of the $Ca + Ca$ and $C + C$ reactions measured by the DLS collaboration (this ratio is actually multiplied by the ratio of $A_p.A_t$ values corresponding to $Ca + Ca/C + C$). We also show on the same figure the DLS data. Of course this comparison can only give a first indication of the relevance of the mechanism mentionned just above. A realistic comparison requires a dynamical calculation incorporating precise experimental acceptance but we believe that the mechanism associated to $\pi - (\Delta - h)_T$ intermediate states, is certainly one important ingredient to account for the observed structure.

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FIGURE CAPTIONS

Figure 1 : Medium corrections to the rho meson propagator in the medium. (1a) : dressing of the pions in the medium. (1b) : vertex correction required by gauge invariance. (1c) : coupling of the rho to quasi-pion and transverse delta-hole states.

Figure 2 : Imaginary part of the rho meson propagator at values of $\rho/\rho_0 = 0, 1, 2$ with imaginary part from Δ resonance and $2p - 2h$ included.

Figure 3 : Ratio of the strength function (multiplied by the ratio of $A_p.A_t$ values for $Ca + Ca/C + C$) for various couples of ρ/ρ_0. Dotted line : 1.8/1.2; dashed line : 2/1; full line : 2.4/1.2. Experimental data obtained by the DLS collaboration [11] are also shown
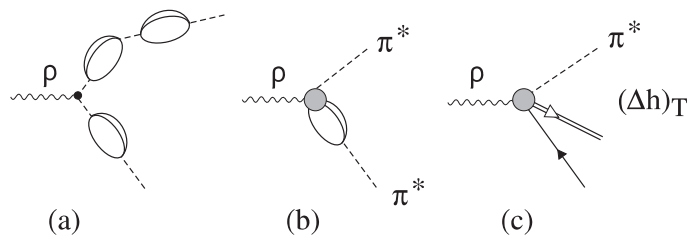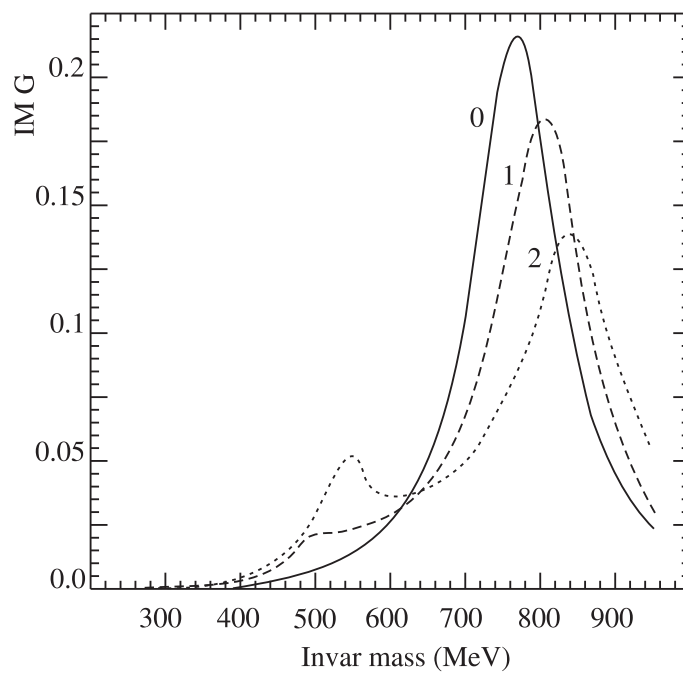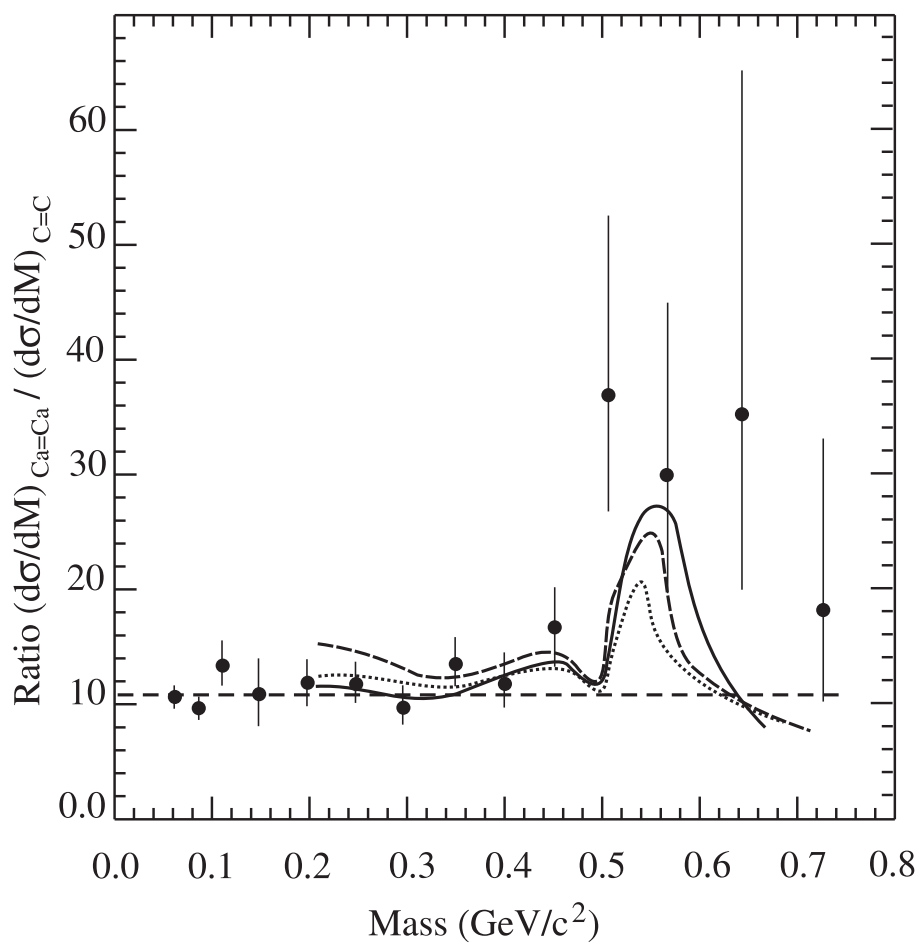
Figure 1:

Figure 2:

Figure 3: